

Quantum corrections to the spin-independent cross section in the inert Higgs doublet model*

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The inert Higgs doublet model is an extension of the standard model with an extra scalar doublet. The extra doublet is Z_2 odd while all the other particles are Z_2 even, thus the model contains a dark matter candidate. It is known that the spin-independent cross section of the dark matter and the nucleon is highly suppressed for $m_{\text{DM}} \sim m_h/2$ at the tree level. In this talk, we show the loop corrections give the significant effects in this regime.

I. INTRODUCTION

One of the reasons why we believe in a model beyond the standard model (SM) is the existence of the dark matter (DM) in our universe. The inert doublet model [2, 3] is a relatively simple model among the models with the DM. In this model, it is known that there are two viable dark matter mass regions, $53 \text{ GeV} \lesssim m_{\text{DM}} \lesssim 71 \text{ GeV}$ and $m_{\text{DM}} \gtrsim 500 \text{ GeV}$ [4–6] under the assumption of the thermal relic abundance scenario [7–9].

In the lighter dark matter case, the dark matter almost annihilate into $b\bar{b}$ as shown in the left panel in Fig. 1. When the dark matter mass is less than half of the Higgs boson mass, the annihilation cross section of this process is enhanced due to the Higgs resonance, and the amount of the dark matter relic abundance getting smaller than the current observed amount of the dark matter [10] unless the DM-Higgs coupling becomes small. Therefore, λ_A should be highly suppressed in the light dark matter mass regime to explain the observed value of the dark matter energy density. The important consequence of the highly suppressed λ_A is the very small spin-independent cross section of the dark matter and the nucleon. The spin-independent cross section is smaller than 10^{-47} cm^2 for $57 \text{ GeV} \lesssim m_{\text{DM}} \lesssim 63 \text{ GeV}$. This makes direct search for the dark matter difficult.

It was pointed out that the quantum corrections via the gauge bosons are significant and the spin-independent cross section is enhanced when the cross section at the tree level is very small [11]. However, the effects from the self-coupling of the inert-doublet and the sign ambiguity of the DM-Higgs coupling were not discussed.

In this talk, we revisit the quantum corrections to the spin-independent cross section in the light dark matter mass regime. We take into account all the relevant diagrams and show the spin-independent cross section highly depends on the self-coupling of the inert-doublet and the sign of the DM-Higgs coupling.

II. MODEL

The inert doublet model¹ includes two scalar fields (H and Φ) which are $\text{SU}(2)$ doublets with $Y = 1/2$. These fields have Z_2 symmetry,

$$H \rightarrow H, \quad \Phi \rightarrow -\Phi. \quad (1)$$

All the other SM fields are unchanged under the Z_2 symmetry. We assume that Φ does not get non-zero vacuum expectation value (VEV). We identify H as the SM Higgs field, and Φ as the *inert* doublet. The new particles are two neutral scalar bosons (S and A) and one charged Higgs boson (H^\pm). All these particles are the components of Φ . The lightest particle among them is stable due to the Z_2 symmetry, thus a neutral scalar is a dark matter candidate as long as the charged Higgs is not the lightest Z_2 -odd particle. We can always interchange S and A by the field redefinition of Φ . Therefore A is generally the dark matter candidate. In the following, we consider the situation that A is the lightest Z_2 -odd particle and is the dark matter candidate.

*This talk is based on Ref. [1].

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¹ A dynamical realization of this model was recently discussed in Ref. [12].

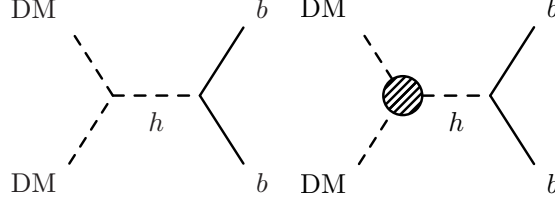


FIG. 1: Diagrams for the dark matter annihilation cross section. The black shaded region means one-loop corrections.

There are five new parameters originated from the Higgs potential. Three of them are the masses of the new particles, $m_A (= m_{\text{DM}}), m_S, m_{H^\pm}$, one is the DM coupling to the SM Higgs boson, λ_A , and the other is the self-coupling of the Z_2 odd particles, λ_2 .

III. LOOP CORRECTIONS TO THE CROSS SECTIONS

Before discussing the quantum corrections to the spin-independent cross section, we have to revisit the dark matter annihilation cross section with loop corrections, because we determine λ_A through the annihilation cross section. We are interested in the dark matter mass region where the annihilation cross section is dominated by the Higgs resonance, thus we consider the diagrams shown in Fig. 1. The cross section is proportional to

$$\sigma v \propto \left| \frac{\lambda_A + \delta\Gamma_h(s) + \delta\lambda_A}{s - m_h^2 + im_h\Gamma_h} \right|^2, \quad (2)$$

where $\delta\Gamma_h(s)$ is the loop correction shown in the right panel in Fig. 1, and $\delta\lambda_A$ is the counterterm. The loop correction depends on s . Since the dominant contributions to the annihilation cross section come from $s \simeq m_h^2$, we take on-shell renormalization condition, namely $\delta\lambda_A = -\delta\Gamma_h(m_h^2)$. Thus almost all the corrections are absorbed into the counterterm, and we find $\langle\sigma v\rangle \propto |\lambda_A|^2$. As a result, we can still use the λ_A determined at the tree level for our purpose.

Now λ_A is determined from the annihilation cross section. But what is actually determined is its absolute value. Thus the sign of λ_A is still unknown, namely λ_A has two solutions, $\pm|\lambda_A|$. This sign ambiguity is not important at the tree level analysis, but it is important for the analysis beyond the tree level, because there are interference terms between the tree diagram and the loop diagrams. We consider both sign possibilities, namely both positive and negative λ_A .

We move to discuss the spin-independent cross section with the loop corrections shown in Fig. 2. The spin-independent cross section is given as

$$\sigma_{\text{SI}} = \frac{1}{4\pi} \frac{(\pm|\lambda_A| + \delta\lambda) \mu^2 m_N^2 f_N^2}{m_A^2 m_h^4}, \quad (3)$$

where m_N is the nucleon mass, μ is the reduced mass in the dark matter and nucleon system, f_N is the form factor, and $\delta\lambda$ is the loop correction given as

$$\delta\lambda = \delta\Gamma_h(0) + \delta\lambda_A + (\text{box and gluon diagrams}). \quad (4)$$

The counterterm is already determined by the annihilation cross section. The momentum transfer in the spin-independent cross section is zero, and different from the annihilation cross section. Thus the total contribution from the vertex correction is $\delta\Gamma_h(0) - \delta\Gamma_h(m_h^2)$. For the contributions from the box and the gluon diagrams, see Ref.[1]. In the case of $m_{H^\pm} = m_S$, we find the fitting formula for $\delta\lambda$,

$$\begin{aligned} \delta\lambda = & -0.00409 \frac{m_{\text{DM}}}{\text{GeV}} \left(0.0000144 - 7.77 \times 10^{-8} \frac{m_{H^\pm}}{\text{GeV}} - 0.00334 \frac{\text{GeV}}{m_{H^\pm}} \right) \\ & + \lambda_2 \left(0.00183 - 7.87 \times 10^{-10} \frac{m_{H^\pm}^2}{\text{GeV}^2} + \frac{m_{\text{DM}}^2}{\text{GeV}^2} \left(-4.13 \times 10^{-8} - 0.00113 \frac{\text{GeV}^2}{m_{H^\pm}^2} \right) \right). \end{aligned} \quad (5)$$

We show the spin-independent cross section with and without the loop correction in Fig. 3. The difference in the three panels is the choice of λ_2 . We find that the loop correction is highly depend on λ_2 , and can be

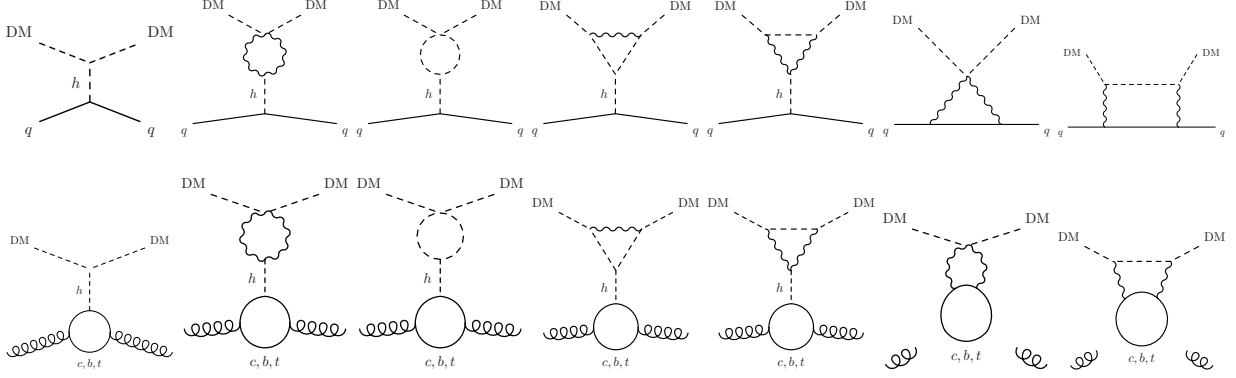


FIG. 2: Diagrams for the spin-independent cross section. The DM-quark interaction diagrams are in the first line, and the DM-gluon interaction diagrams are in the second line. The diagrams in the most left give leading order contribution if λ_A is not suppressed.

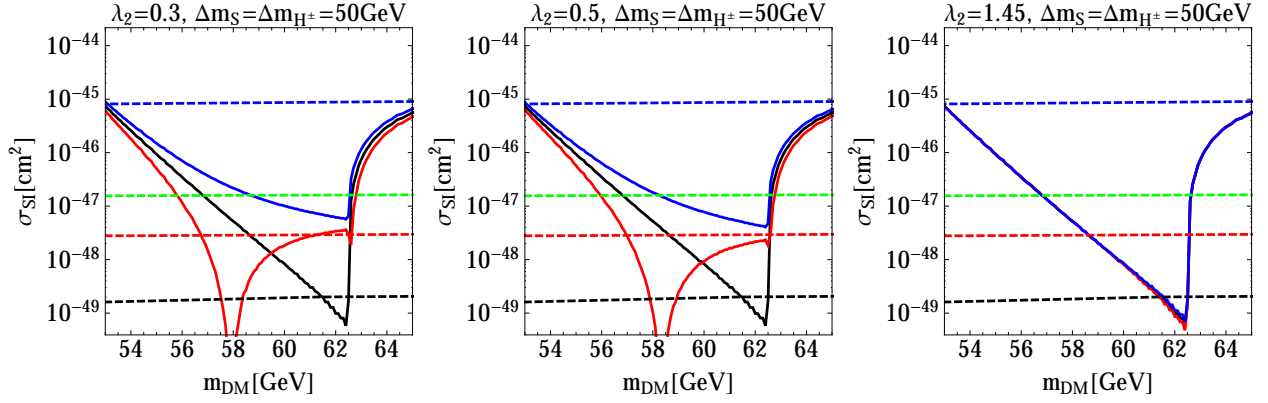


FIG. 3: The spin-independent cross section as a function of the DM mass. The black line is the result without the loop corrections. The red (blue) line is with the loop corrections and the sign of λ_A is positive (negative). The blue-dashed line is the current LUX bound [13]. The green-dashed, red-dashed lines are the future prospect by XENON1T [14] and LZ [15], respectively, and the black-dashed line is the discovery limit caused by atmospheric and astrophysical neutrinos [16]. Here we take $m_{H^\pm} = m_S = m_{DM} + 50$ GeV.

accidentally canceled out. We vary the value of λ_2 for $0 < \lambda_2 < 1.45$ in Fig. 4, because we do not know the value of λ_2 . The yellow region in the plot is the prediction of the spin-independent cross section in this model. The dependence of the m_{H^\pm} and m_S are shown in Fig. 5. We find that these two parameters also affect the prediction.

IV. SUMMARY

We investigate the quantum corrections to the spin-independent cross section in the inert-doublet model. The corrections are significant for the light dark matter regime, $53 \text{ GeV} \lesssim m_{DM} \lesssim m_h/2$, where the DM-Higgs couplings is highly suppressed. We find the loop corrections significantly modify the prediction based on the tree level analysis. At the tree level analysis, the spin-independent cross section depends only on the dark matter mass after setting the DM-Higgs coupling by the relic abundance. However, at the loop level, it depends on the other model parameters as well. Especially, the effect from λ_2 and the sign ambiguity of λ_A are significant.

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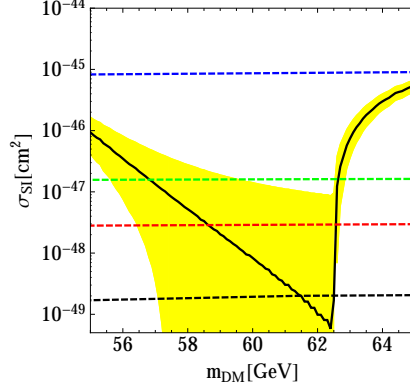


FIG. 4: The spin-independent cross section at tree level (black-solid line), and loop level (yellow shaded region). Here we vary λ_2 for $0 < \lambda_2 < 1.45$. The meaning of the dashed lines are the same as in Fig. 3. Here we take $\Delta m_{H^\pm} = 50$ GeV, $\Delta m_S = 50$ GeV.

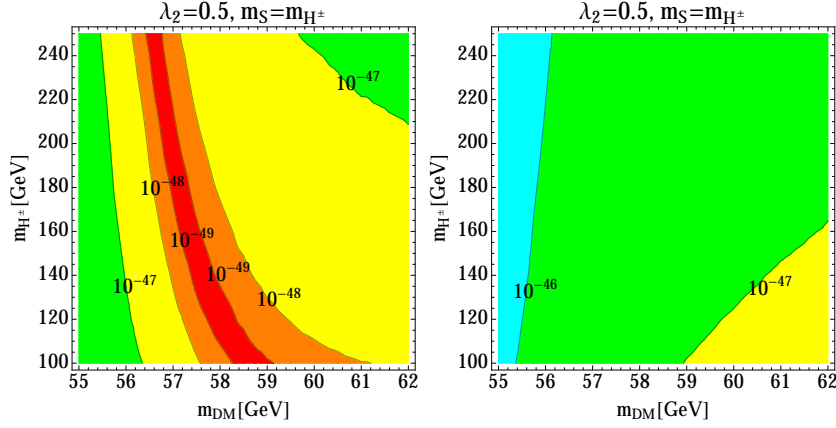


FIG. 5: The σ_{SI} in (m_{DM}, λ_2) -plain. The value on the panels is σ_{SI} in cm^2 unit. In the left (right) panel, the sign of the λ_A is positive (negative).

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